Attachment 1
The San Juan Basin

The San Juan Basin covers an area of about 7,500 square miles across the Colorado-New Mexico line in the Four Corners region (Figure A1-1). It measures roughly 100 miles long in the north-south direction and 90 miles wide. The Continental Divide trends north-south along the east side of the basin, and land surface elevations within the basin range from 5,100 feet on the western side to over 8,000 feet in the northern part.

The San Juan Basin is the most productive coalbed methane basin in North America. Coalbed methane production in the San Juan Basin totaled over 800 billion cubic feet in 1996 (Stevens et al., 1996). This number rose to 925 billion cubic feet in 2000 (GTI, 2002). The coals of the Upper Cretaceous Fruitland Formation range from 20 to over 40 feet thick. Total net thickness of all coalbeds ranges from 20 to over 80 feet throughout the San Juan Basin. Methane production in the San Juan Basin averages about 800 thousand cubic feet per day per well, whereas wells average 120 thousand cubic feet per day in the Black Warrior basin in southeastern United States (Stevens et al., 1996). Coalbed methane production occurs primarily in coals of the Fruitland Formation, but some coalbed methane is trapped within the underlying and adjacent Pictured Cliffs Sandstone, and many wells are completed in both zones. Coalbed methane wells in the San Juan Basin range from 550 to 4,000 feet in depth, and about 2,550 wells are currently operating (CO Oil and Gas Conservation Commission and NM Oil Conservation Division, 2001).

1.1 Basin Geology

The San Juan Basin is a typical asymmetrical, Rocky Mountain basin, with a gently dipping southern flank and a steeply dipping northern flank (Figure A1-2) (Stone et al., 1983). The Fruitland Formation is the primary coal-bearing unit of the San Juan Basin and the target of most coalbed methane production. Geologic cross sections showing detailed relationships between the Fruitland Formation adjacent rocks in different parts of the basin are shown in Figures A1-3, A1-4, A1-5 and A1-6. The Fruitland coals are thick, with individual beds up to 80 feet thick. The Fruitland Formation is composed of interbedded sandstone, siltstone, shale, and coal. The stratigraphy of the Fruitland Formation is predictable throughout the basin, as follows:

- The thickest coalbeds are always found in the lower third of the formation;
- Pictured Cliffs Sandstone occurs immediately below the formation;
- Sandstone content is greater in the lower half; and
- Siltstone and shale predominate in the upper half (Choate et al., 1993).

The San Juan Basin may be subdivided into three unique regions, based on similar geologic, hydrologic, and production characteristics (Figure A1-7). These regions are, denoted as Area 1, Area 2, and Area 3 are described in more detail below (Kaiser and Ayers 1994).

Area 1 consists of the northwestern quarter of the basin. Area 1 is characterized by the thickest (>20 feet) and highest-rank coal deposits in the San Juan Basin (Ayers et al., 1994). Most wells produce more than 1,000 cubic feet per day and several wells produce more than 15,000 cubic feet per day. Almost 90 percent of total methane production from the Fruitland Formation comes from three fields in a region of Area 1 known as the "Fairway" (Young et al., 1991; Ayers et al., 1994). Area 1 is an area of active recharge and in most places is hydrostatically over-pressured (greater than 0.50 pounds per square inch per foot). Wells in Area 1 usually produce moderate to large volumes of water, some of which meet the quality criteria of less than 10,000 mg/L TDS for a USDW (Kaiser et al., 1994).

Area 2 (the west-central region of the San Juan Basin) is hydrostatically under-pressured (0.30 to 0.50 pounds per square inch per foot) and is an area of regional groundwater discharge. Coal beds are usually seven to 15 feet thick, and occur primarily in northwest-trending belts that extend to the southwestern margin of the basin. Methane production from wells can be more than 100 thousand cubic feet per day, and a few wells produce 200 to 500 thousand cubic feet per day. Methane gas is produced water-free in this area as a consequence of the hydrostratigraphy and trapping mechanisms (Kaiser and Ayers, 1994). Additionally, Kaiser and Ayers (1994) suggest that water may be less mobile in the hydrophilic and low permeability coals. The Fruitland Formation in this area where it is underpressured generally show the presence of NaCl-type waters (Kaiser et al., 1994) that most likely have TDS concentrations greater than 10,000 mg/L, which does not meet the criteria for a USDW.

Area 3, the eastern region of the San Juan Basin, is hydrostatically under-pressured, and features low permeability and low hydraulic gradient, which suggests slow water movement within most of the aquifer. Only a few coalbed gas wells are located in this part of the basin, and they produce up to eight thousand cubic feet of methane per day, with little or no water content (Kaiser and Ayers, 1994). Produced waters from the Fruitland Formation in most of Area 3 have a high-salinity, resembling seawater (Kaiser and Ayers, 1994) in which TDS are too high to meet the water quality criteria of a USDW. However, along the southern margin of Area 3, TDS concentrations are less than 10,000 mg/L (Kaiser and Swartz, 1994).

1.2 Basin Hydrology and USDW Identification

Tertiary sandstones and Quaternary alluvial deposits are present at the surface over much of the basin interior. These serve as the primary drinking water aquifers in the basin (Figure A1-2), and produced 55 million gallons per day in 1985 (Wilson, 1986). Cretaceous sandstones are an important source of water on the basin's periphery (Choate et al., 1993). The Paleocene Ojo Alamo Sandstone yields as much as 30 gallons per minute of potable water (Hale et al., 1965) and is mentioned as one of the primary drinking water aquifers of the region (Brown and Stone, 1979). Cleats and larger fractures in the Fruitland coals and the presence of interbedded permeable sandstones make the Fruitland Formation an aquifer and source of drinking water along the northern margin of the basin where TDS in the groundwater are less than 10,000. In most of Area 1 both the Fruitland Formation and the underlying upper Pictured Cliffs Sandstone act as a single hydrologic unit (Kaiser et al., 1994). The Fruitland and upper Pictured Cliffs Sandstone aquifer is underlain and confined by the low-permeability main Pictured Cliffs Formation and is overlain and partly confined by the Kirtland shale, which is up to 1,000 feet thick in the central basin. Overlying the Kirtland formation is the Ojo Alamo Sandstone, (Figures A1-4, A1-5 and A1-6) which has been suggested as a possible source of ground water for the municipality of Bloomfield (Stone, et a., 1983). At Bloomfield the coal and gas bearing Fruitland is separated from the Ojo Alamo aquifer by the Kirtland shale.

In the northern part of the basin the Fruitland Formation and the underlying upper Pictured Cliffs Sandstone act as a single hydrologic unit because on a large scale they contain the same hydraulic head and water quality characteristics and are the source of both the water and gas in the Pictured Cliffs sand tongues (Ayers and Zellers, 1994; Ayers et al., 1994). However, compartmentalization occurs at a smaller scale due to pinch out of thick, laterally extensive coal seams and to truncation and offset of the beds by faults. Hydrologic compartmentalization of the aquifer is reflected as areas of over-pressuring (less than 0.5 pounds per square inch per foot), abrupt changes in potentiometric surface (Figure A1-8), and upward flow (Kaiser et al., 1994). Kaiser et al., (1994) describe hydrologic conditions in the northern part of the basin "The Fruitland is postulated to behave regionally as a homogeneous, hydraulically interconnected aquifer, or single hydrologic unit, and locally as a heterogeneous disconnected aquifer."

In general, ground water is recharged along the Fruitland outcrops at the elevated, west, northern, and northwestern margins of the basin, and lateral flow converges primarily from the northeast and southeast toward upward discharge to the San Juan River valley (Kaiser et al., 1994). In the north, the Fruitland and upper Pictured Cliffs Sandstone aquifer system is confined by the overlying Kirtland shale, but it is poorly confined by the Kirtland in the central and southern portions of the basin. Water from the Fruitland discharges in the western part of the basin and migrates upward across the Kirtland shale into the Animas and San Juan Rivers (Stone et al., 1983). Generalized ground water movement in the Fruitland system is shown in cross-section and plan view in Figures A1-9 and A1-10 (Kaiser and Swartz, 1988). The results of ground water flow modeling for the entire basin (Kaiser et al., 1994) are shown in Figure A1-11.

In most of Area 1 the Fruitland system produces water containing less than 10,000 mg/L TDS, the water quality criteria for a USDW. Ground water is usually freshest at the outcrop in recharge areas. Because the water chemistry evolves along its flow path, dissolving salts and mixing with formation water as it flows, the ground water becomes increasingly saline as distance from the recharge source increases. The presence of low-salinity water at given locations in the San Juan Basin usually marks close proximity to the recharge source or the most permeable flow paths and implies a dynamic, active aquifer system (Kaiser et al., 1994). Figure A1-12 shows the chloride concentration of ground water in the Fruitland Formation, and indicates that water nearest the northern recharge areas has a low dissolved solids and chloride content. Kaiser et al. (1994)

reported that wells in the northern part of Area 1 produced water containing from 180 to 3,015 mg/L TDS. This was found to be the case over large portions of Area 1, especially within freshwater plumes resulting from areas of high permeability or fracture trends (Kaiser and Swartz, 1990; Oldaker, 1991).

Kaiser and Swartz, 1994 conducted a water-quality sampling program in the San Juan Basin. Analyses taken from Fruitland coal wells in Area 1 show that the majority of wells (16 of 27 wells) produce water containing less than 10,000 mg/L TDS, (Figures A1-13a & A1-13b), although some nearby wells thought to be in less permeable zones produce water with higher TDS concentrations up to 23,000 mg/L (Kaiser et al., 1994). The boundary between waters with more and less than 10,000 TDS has not been published. Another group of wells throughout the same area was also sampled, but these wells were completed (constructed) in the adjacent and underlying Pictured Cliffs Sandstone bodies, which are in hydrologic communication with the Fruitland system (Kaiser et al., 1994).

Although from the above information it would seem that the Fruitland would be classified a USDW, the following additional information about disposal of brackish water produced along with the methane would seem to indicate that most of the water in the Fruitland would not meet the TDS criteria for USDW. Coalbed methane wells in the San Juan Basin produced from zero to over 10,500 gallons of water per day, which contain from less than 300 mg/L TDS to over 25,000 mg/L (Kaiser et al., 1994; Kaiser and Ayers, 1994). Brackish water of various TDS concentrations and brine are produced in the overpressured Area 1 of the basin while virtually no water is produced from coalbed methane wells in Areas 2 and 3 of the basin. Cox, (1993) reported "Water disposal in the San Juan basin is a significant, long-term issue." In 1992, coalbed methane wells produced over 5 million gallons of water per day, and production was expected to increase to over 7.5 million gallons per day by 1995 (Cox, 1993). Produced water is disposed of by means of evaporation ponds, or, more commonly, by Class II injection into deeper zones such as the Entrada and Bluff sandstones, Morrison Formation, and Mesa Verde sandstone (Kaiser and Ayers, 1994). They estimated that injection wells cost up to $2 million each and Cox reported that 51 of them had been constructed in the basin by 1993. Based on these expenses, much of the water produced with the methane is surely not of drinking water quality, and may possibly not be of USDW quality.

Area 2 is primarily an area of ground water discharge. The Fruitland coals and Pictured Cliffs Sandstone in Area 2 are in hydraulic communication and behave as a single aquifer. The aquifer is under-pressured (less than 0.50 pounds per square inch per foot), transmits ground water from the northeast and southeast, and eventually discharges to the Animas and San Juan rivers. TDS of most samples from Area 2 ranges from 10,000 to 16,000 mg/L (Kaiser et al., 1994).

The Fruitland system in most of Area 3 contains slow-moving water with salinity approximately equal to that of seawater, greater than 25,000 mg/L TDS, (Kaiser & Ayers, 1994). In Area 3, the Fruitland and Pictured Cliffs are separate, confined aquifers. In the southeastern one-third of Area 3, the Kirtland shale is absent because of Tertiary-age erosion, and the Fruitland and Ojo Alamo Sandstone could be in hydraulic communication with one another (Figure A1-6). In this area Tertiary rocks, including the Ojo Alamo, are mapped by the USGS (Figure A1-14) as an aquifer having water with dissolved solids ranging from 500 to 1,000 mg/L (Lyford, 1979).

At the basin's southern margin in Area 3, downward flow occurs from the Ojo Alamo through the Kirtland shale to the poorly confined Fruitland aquifer through which it then moves southward to outcrops at a lower elevation and northward to the San Juan River Valley (Kaiser et al., 1994) (Figure A1-11). Twenty four of 26 water samples from the Fruitland/Pictured Cliffs aquifer system in the south margin of the basin reported by Kaiser and Swartz (1994) had less than 9,000 mg/L TDS (Figure A1-13e & A1-13f). Ground water in the Fruitland Formation at the southern margin of the basin has less than 10,000 mg/L TDS because most recharge there comes from above the Kirtland formation, rather than from southward throughput from the Fruitland Formation.

1.3 Coalbed Methane Production Activity

Coalbed methane production occurs primarily in coals of the Fruitland Formation. However, some methane is trapped within the underlying and adjacent Pictured Cliffs Sandstone, therefore many wells are completed in both zones. In 1993, about 2,550 wells were operating in the San Juan Basin coalbed methane development area. All wells were vertical wells that range from about 500 to 4,000 feet in depth, and were drilled using water or water-based muds. Almost every well has been fracture-stimulated, using either conventional hydraulic fracturing in perforated casing or cavitation cycling in open holes (Palmer et al., 1993a). Total gas production was 925 billion cubic feet in 2000 (GTI, 2002).

Cavitation cycling is a fracturing method unique to a small area of the north-central San Juan Basin called the "Sweet Spot" or Fairway of Area 1 (Figure A1-15). Almost half of all San Juan wells are located within the Fairway area and utilize open-hole completions (no casing across the production interval) and cavitation cycling. Cavitation cycling is used in this area because coals are: 1) very thick (individual coals over 40 feet thick), 2) hydrostatically over-pressured (0.5 to 0.7 pounds per square inch per foot), and 3) relatively more permeable than the rest of the basin (and coals in other basins) (Palmer et al., 1993a). This method uses several mechanisms to link the wellbore to the coal fracture system. Cavitation cycling:

- Creates a physical cavity in the coals of the open-hole section (up to 10 feet in diameter);
- Propagates a self-propping, vertical, tensile fracture that extends up to 200 feet away from the wellbore (parallel to the direction of least stress); and
- Creates a zone of shear stress-failure that enhances permeability in a direction perpendicular to the direction of least stress (Palmer et al., 1993; Khodaverian and McLennan, 1993) (Figure A1-16).

Cavitation is accomplished by applying pressure to the well using compressed air or foam, and then abruptly releasing the pressure. The over-pressured coal zones provide a pressure surge into the wellbore (a "controlled blowout"), and the resulting stress causes dislodgement of coal chips and carries the chips up the well. These cycles of pressure and blowdown are repeated many times over a period of hours or days, and the repeated, alternating stress-shear failure in the coal formation creates effects that extend laterally from the wellbore (Kahil and Masszi, 1984). The resulting vertical fracture is tensile in origin, that is, it results from a "pulling" force rather than the compressive forces that create conventional hydraulic fractures. Because the fracture is tensile in origin, the height of the fracture does not usually extend out of the target coal seam (Logan et al., 1989).

Wells outside the Fairway area utilize cased-hole, perforated completions that employ conventional hydraulic fracturing (Holditch, 1990). Hydraulic fracturing in the San Juan Basin uses between 55,000 to 300,000 gallons of stimulation and fracturing fluids and between 100,000 to 220,000 pounds of sand proppant (Palmer et al., 1993). Fracturing in coal basins in eastern United States typically links multiple, thin coal seams by a single fracture up to 600 feet high (Hanson et al., 1987; Jones et al., 1987; Saulsberry et al., 1990). On the other hand, in the San Juan Basin geologic conditions in conjunction with fracturing techniques usually produce vertical fractures much longer than they are high, for example, up to 400 feet radially and less than 150 feet high (e.g., Colorado 32-7 No. 9 well, La Plata county, CO; Mavor et al., 1991). The primary reasons for the controlled height of San Juan coalbed fractures are the thickness and close spacing of coal seams (obviating the need for excessive height), and the presence and petro-physical properties of the overlying Kirtland shale (which prevents inadvertent fracture excursion out of the Fruitland) (Jeu et al., 1988; Logan et al., 1989; Palmer and Kutas, 1991). Holditch (1993) reported, however, that hydraulic fractures in the San Juan Basin can grow into overlying beds where the coal seam is not overlain by shale.

Fassett (1991) found that coalbed methane can migrate into overlying USDWs near the northern outcrop, in areas where confining shale layers are absent. Because of these factors, hydraulic fracturing in the San Juan Basin may indirectly impact overlying USDWs near the Fruitland outcrop at the basin margins, where USDWs are in closer proximity and the Kirtland shale may be eroded. Near the northern and northwestern recharge zones, ground water usually contains less than 3,000 mg/L TDS (Kaiser et al., 1994 and Cox et al., 1995).

Fracturing and stimulation fluids utilized in the northern San Juan Basin include (Figure A1-17and Table A1-1):

- Hydrochloric acid (12% to 28% HCl);
- Plain water;
- Slick water (water mixed with solvent);
- Linear gels (water and a thickener such as guar-gum or a polymer);

- Cross-linked gels with breakers (gels with additives to prevent fluid leak-off from the fracture, and "breaker" chemicals to reduce viscosity so that the gel can be produced back from the well after treatment); and
- Nitrogen and CO_2 foam (75 percent gas, 25 percent water or slick water, plus a foaming agent) since about 1992 (Harper, 1985; Jeu et al., 1988; Holditch et al., 1989; Palmer et al., 1993; Choate et al., 1993)

Oilfield service companies supply the stimulation fluid used to fracture the well as part of the service. The chemical composition of many fracturing fluids may be proprietary, and EPA was unable to find complete chemical analyses of any fracturing fluids in the literature. Table A1-1 presents some data from the literature concerning the general chemical makeup of common San Juan fracturing fluids (Economides and Nolte, 1989; Penny et al., 1991). In addition, most gel fluids utilize a breaker compound (usually borate or persulfate compounds or an enzyme, at two lb/1,000 gal) to allow post-treatment thinning and easier recovery of gels from the fracture (e.g., Jeu et al., 1988; Palmer et al., 1993; Pashin and Hinkle, 1997).

Many of the compounds listed in Table A1-1 may be harmful to human health if ingested with drinking water. Coalbed methane development by fracturing, and stimulation in the San Juan Basin are regulated by the Colorado Oil and Gas Conservation Commission and the New Mexico Oil and Gas Board. Based on an analysis of current regulations, neither agency regulates the type or amount of fluids used for fracturing (Colorado State Oil and Gas Board Rules and Regulations 400-3, 2001; New Mexico Energy, Minerals and Natural Resources Department, Oil Conservation Division Regulations Title 19, Chapter 15, 2001).

About half of the coalbed methane wells in Area 1 are located in the Fairway zone and feature "cavitation-cycling" completions (Palmer et al., 1993) (Figure A1-15). Therefore, about half of the wells in Area 1 have probably been stimulated using conventional fracture treatments. Based on the well density of Area 1 in 1990 (Figure A1-18) compared to the current well population (2,550 wells), it is estimated that between 700 and 1,000 coalbed methane wells have been fracture-stimulated in the USDW of Area 1.

Injection of these fluids is temporary and the majority of fracturing fluid is subsequently pumped back up through the well when development or production is initiated. Because of the heterogeneous, stratified, and fractured nature of coal deposits, it is likely that some volume of fracturing fluids is "stranded" in zones that were not completely propped. Similarly, natural or propagating fractures may open and allow fluids to flow through during high fracturing pressure, but subsequently trap the fluids as they close after fracturing pressure decreases (the "check-valve" effect) (Warpinski et al., 1988; Palmer et al., 1991). Contrary to conventional formations where fluid invasion may penetrate only a few inches, fracturing fluids in coal can penetrate into the surrounding formation (as "leak-off") as much as 50 to 100 feet away from the fracture (Palmer et al., 1991; Puri et al., 1991) (Figure A1-20). In these and other cases, when fracturing ceases and production resumes, these chemicals may not be entirely pumped back out of the coalbed methane well, and are therefore might be available to migrate through the aquifer.

There are very few data in the literature concerning the volume of fracturing fluids subsequently pumped back to the well after stimulation has ceased. Mukhergee et al. (1995) observed that for fracture stimulations in layered formations, only 35 to 45 percent of fracturing fluids are recovered. Palmer et al. (1991) found that only 68 percent of fracturing fluids were recovered during subsequent production of a coalbed well in Alabama. What percentage of the injected fluid is recovered and what percentage become truly stranded is unknown. In the case of producing wells, water quality threats from unrecovered fluids would seem to be small because production maintains a gradient to the well and the produced water is disposed of in conformance with protective regulations. In the case of wells that have not been completely developed and/or placed in production, gradients would return to the natural pre-construction conditions and then the fluids might be free to migrate.

It has been shown that methane can migrate from gas wells into aquifers along the northern margin of the basin, but this condition was remediated with improved gas well construction (Cox et al., 1995). In addition, wells completed in other aquifers in the outcrop area have been shown to produce water chemically and isotopically similar to Fruitland wells, implying communication between the formations (Cox et al., 1995).

1.4 Summary

Coalbed methane development and hydraulic fracturing in some of the northern portions of the San Juan Basin take place within a USDW. The waters of the Fruitland-upper Picture Cliffs aquifer and producing zone in Area 1 usually contain less than 10,000 mg/L TDS. Most waters in the northern half of Area 1 contain less than 3,000 mg/L, and wells near the outcrop produce water that contains less than 500 mg/L.

Each fracture stimulation treatment may inject, on average, approximately 120,000 to 270,000 gallons of fracturing fluid per treatment. There are no state controls on the type, composition, or volume of fracturing fluid employed in each well or treatment. In contrast to conventional gas formations, the anisotropic nature of fracture permeability, the volume of treatment fluids employed, and the height and proppant distribution in coalbed fractures may prevent the effective recovery of fracturing fluids during subsequent production. Whether these unrecovered fluids remain truly stranded is unknown. A few water samples from the Fruitland aquifer show possible evidence of residual contamination from previous fracturing treatments, suggesting that fracturing fluids might not always be fully recovered.

The potential for fracturing to cause or allow degradation of water in aquifers adjacent to the producing zones seems relatively remote in the currently active gas producing fields, but the potential varies in different parts of the basin. It has been shown that methane can migrate from gas wells into aquifers along the northern margin of the basin, but this condition was corrected with improved gas well construction. There is little potential for fracturing to create communication between the Fruitland-upper Picture Cliffs aquifer and the Ojo Alamo aquifer over much of the basin because they are separated by the poorly permeable Kirkland shale. However, the Kirkland varies greatly in thickness and forms a leaky hydrologic barrier. In the eastern part of the basin the Kirkland formation has been eroded and the Ojo Alamo lies disconformably and directly upon the Fruitland Formation potentially allowing fracturing to cause hydraulic communication between the saline waters of the Fruitland and the fresh waters (500 to 1,000 mg/L) of the Ojo Alamo.

Table A1-1. Chemical Components of Typical Fracture/Stimulation Fluids Used for San Juan Coalbed Methane Wells

Type of Stimulation Fluid	Composition	pH
Hydrochloric acid	15% HCl water solution	<1-3
"Slick" water	miscible or immiscible solvent as viscosity reducer (% unknown)	NA
Diesel oil	NA	NA
Gels[1]		
R-F	3% resorcinol, 3% formaldehyde, 0.5% KCl, 0.4% $NaHCO_3$	6.5
Pfizer Flocon 4800	0.4% xanthan, 154 ppm Cr^{3+} (as $CrCl_3$), 0.5% KCl	4.0
Marathon MARCIT	1.4% polyacrylamide (HPAM), 636 ppm Cr^{3+} (as acetate), 1% NaCl	6.0
DuPont LuDox SM	10% colloidal silica, 0.7% NaCl	8.2
CPAM crosslinked with Pfizer Floperm 500	0.4% cationic polyacrylamide (CPAM), 1520 ppm glyoxal 2% KCl	7.3
Drilling Specialties HE-100 Crosslinked	0.3% HPAM-AMPS, 100 ppm Cr^{3+} (as acetate), 2% KCl	5.0
Dowell YF-230	Hydroxypropylguar (HPG) x-linked with borate, persulfate with amine	NA

[1] Gels are typically mixed at a ratio of 40 lbs. per 1000 gal. water; compositions shown are "as mixed".

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SPE = Society of Petroleum Engineers

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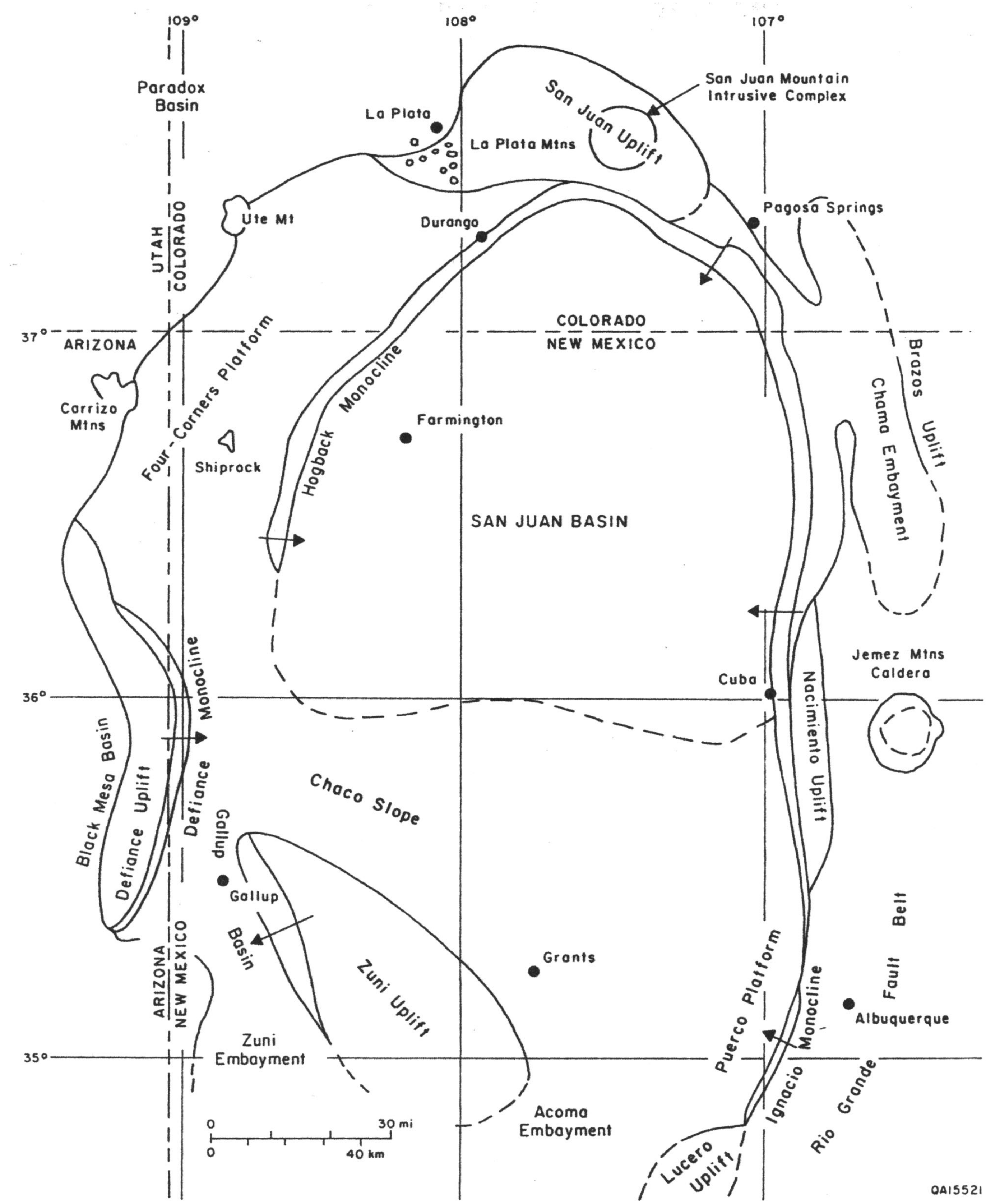
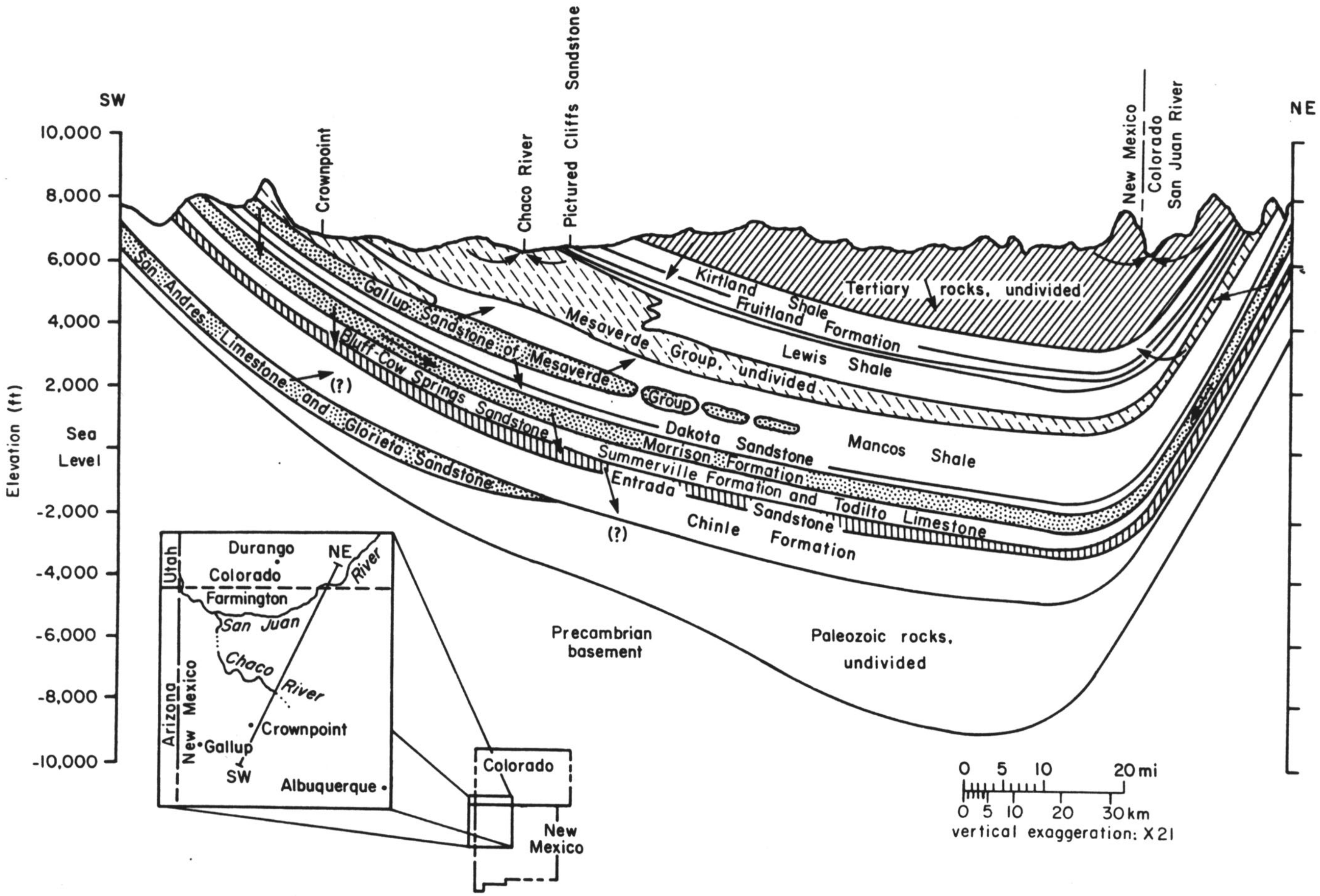


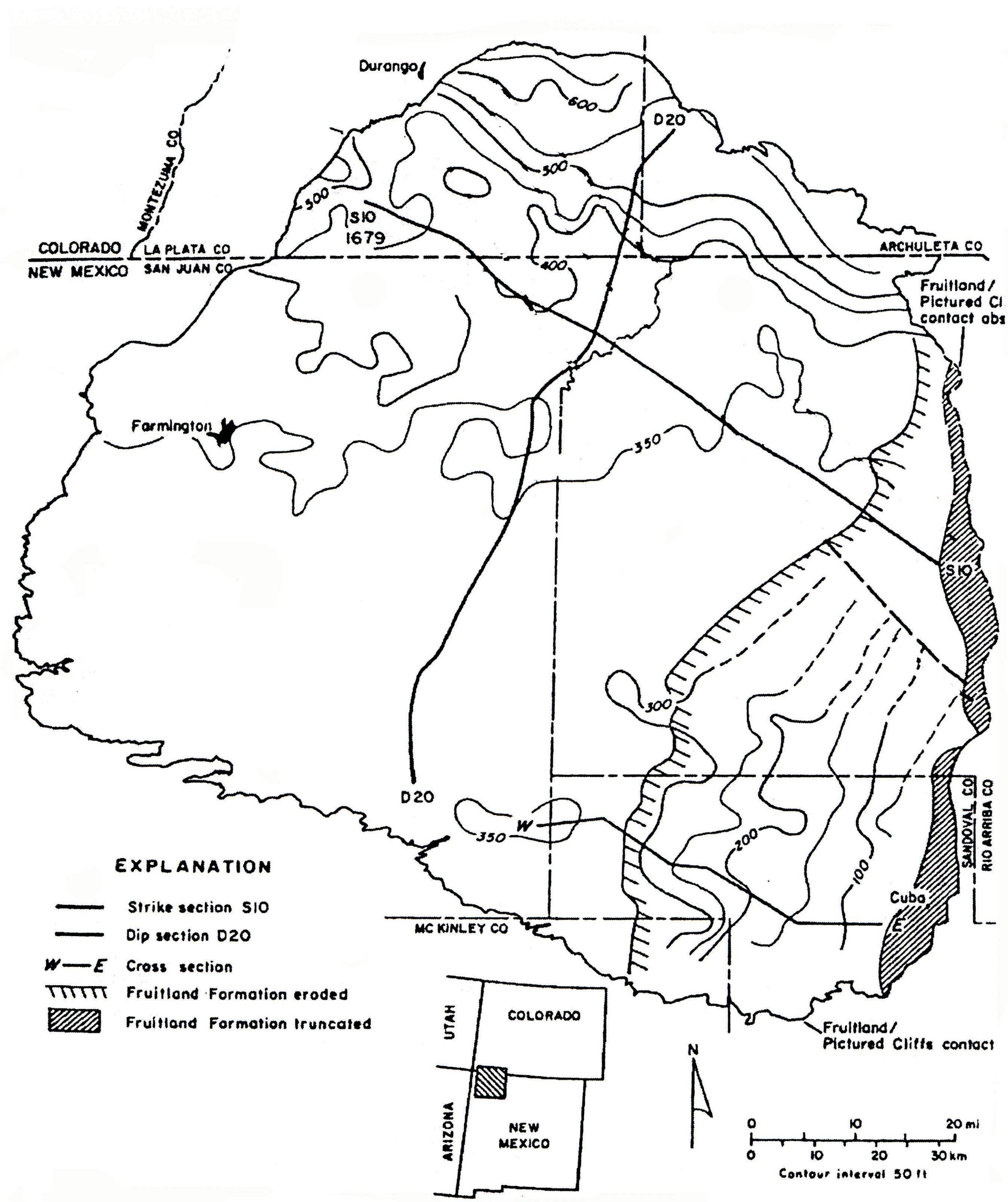
Regional Tectonic Setting of the San Juan Basin
(Laubach & Tremain, 1994)

7/14/01 kk 1027-SJ-1.cdr	Figure A1-1



Generalized Hydrogeologic Cross-Section of the San Juan Basin (Stone et al., 1983)

7/14/01 kk 1027-SJ-2.cdr	Figure A1-2

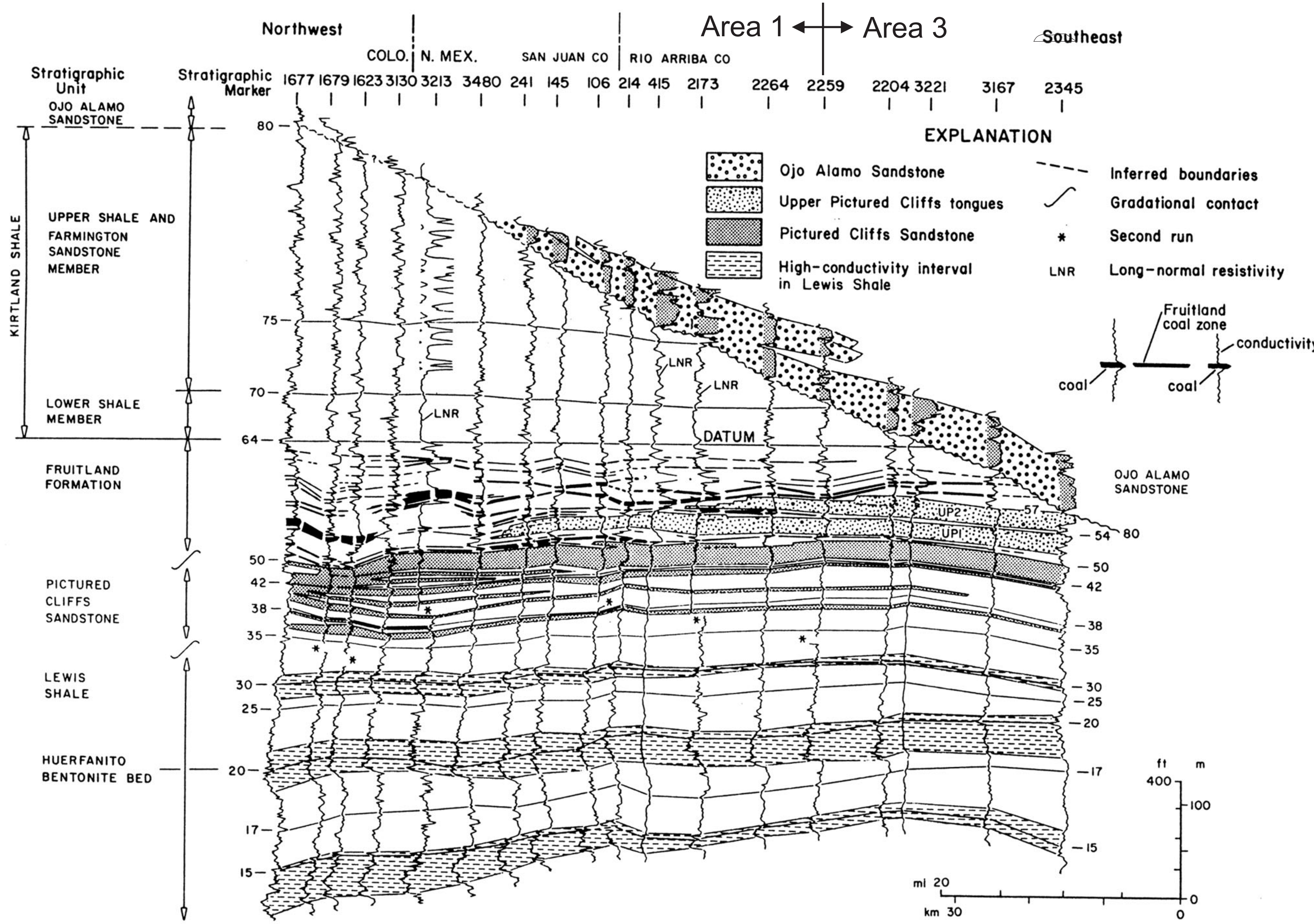


Isopach Map of the Fruitland Formation Including Pictured Cliffs Tongues.

Cross Sections S10, D20 and E-W are shown in Figures A1-4,A1-5 and A1-6

(Ayers and Ambrose, 1990)

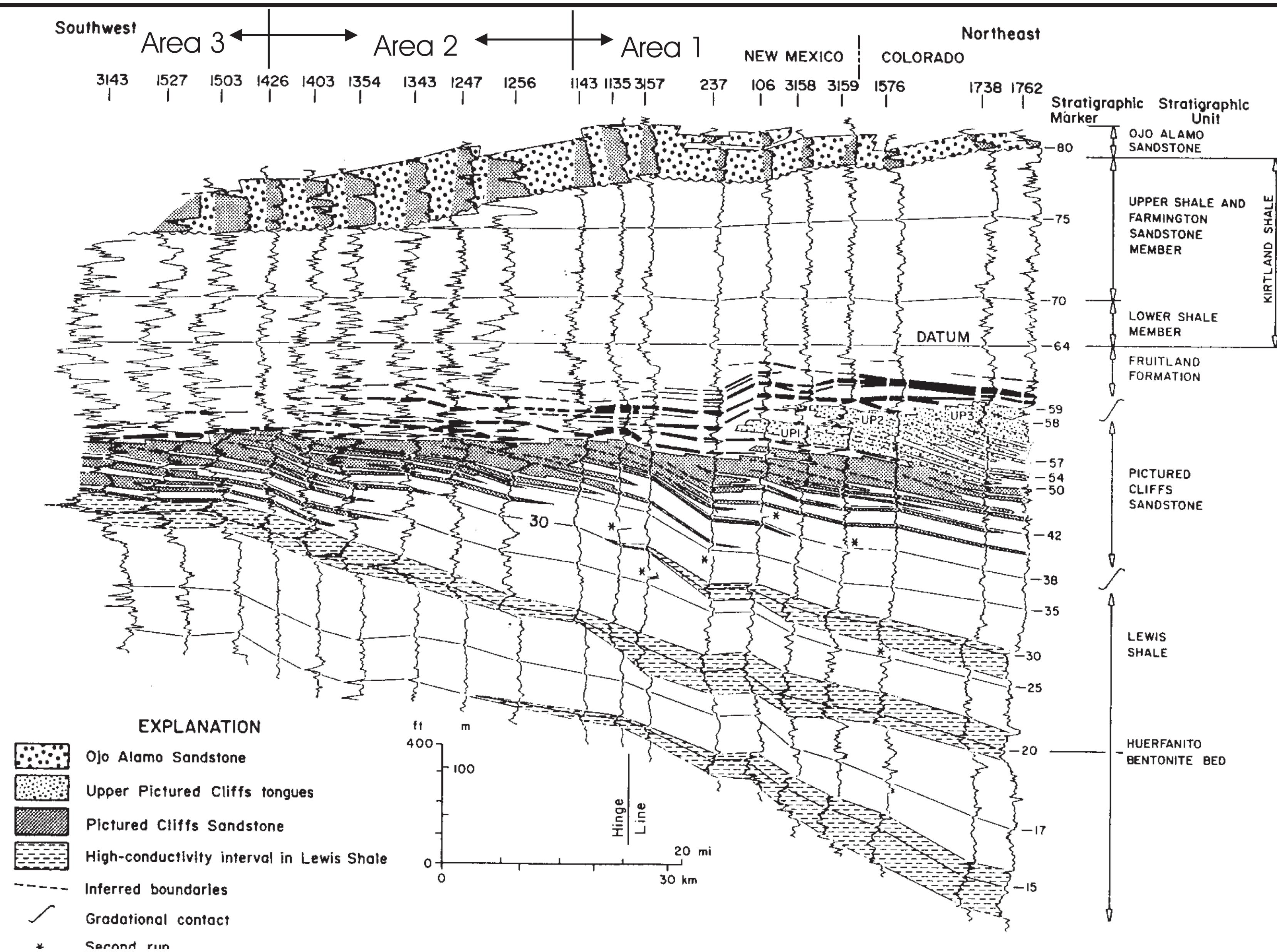
7/14/01 kk 1027-SJ-3.cdr	Figure A1-3



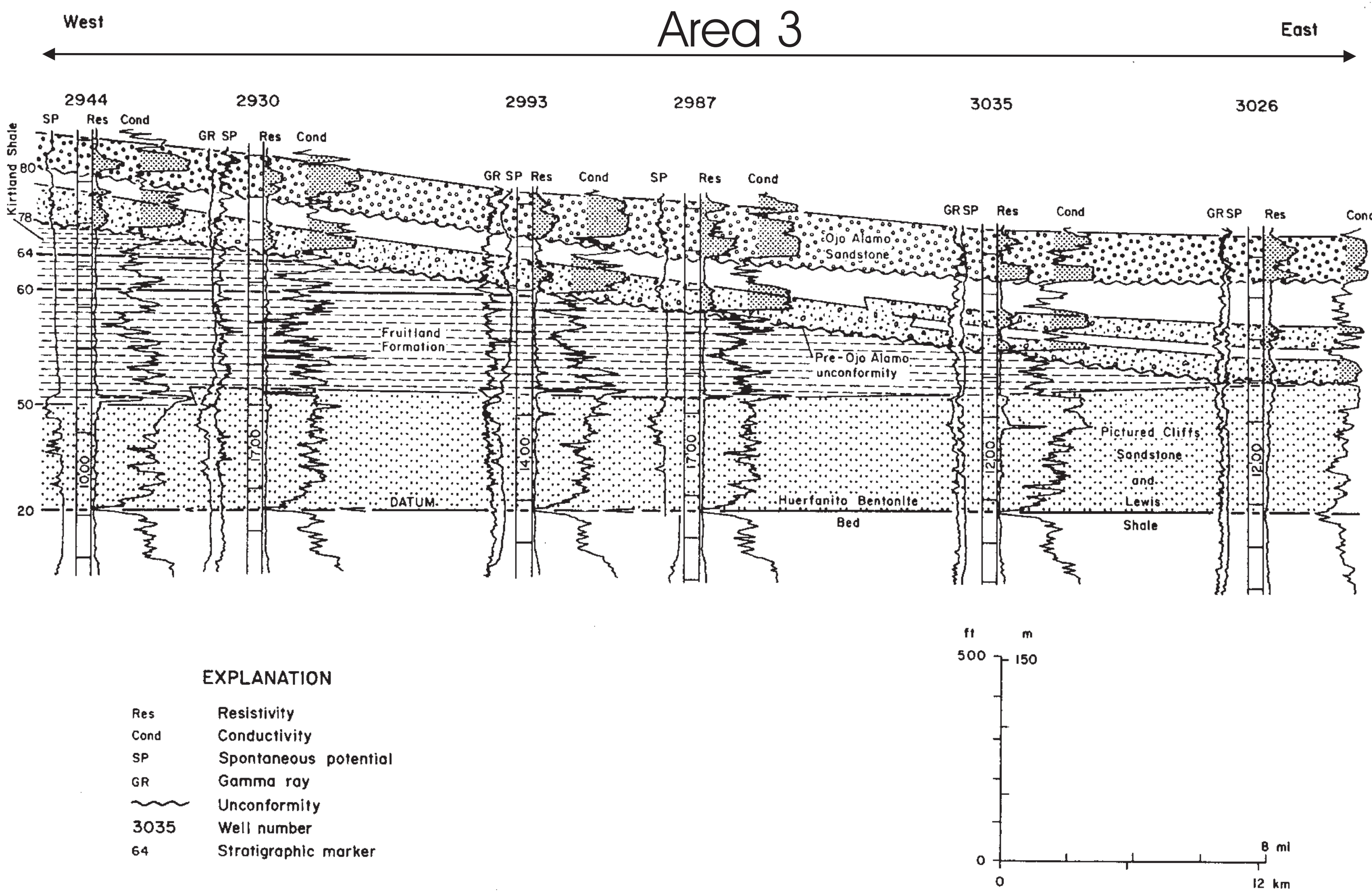
Cross Section S-10 from Figure A1-3, a Stratigraphic Strike Section (Ayers and Ambrose, 1990)

7/14/01 kk 1027-SJ-4.cdr

Figure A1-4



Cross Section D-20 from Figure A1-3, a Stratigraphic Dip Section from the Fruitland to the Ojo Alamo (Ayers and Ambrose, 1990)



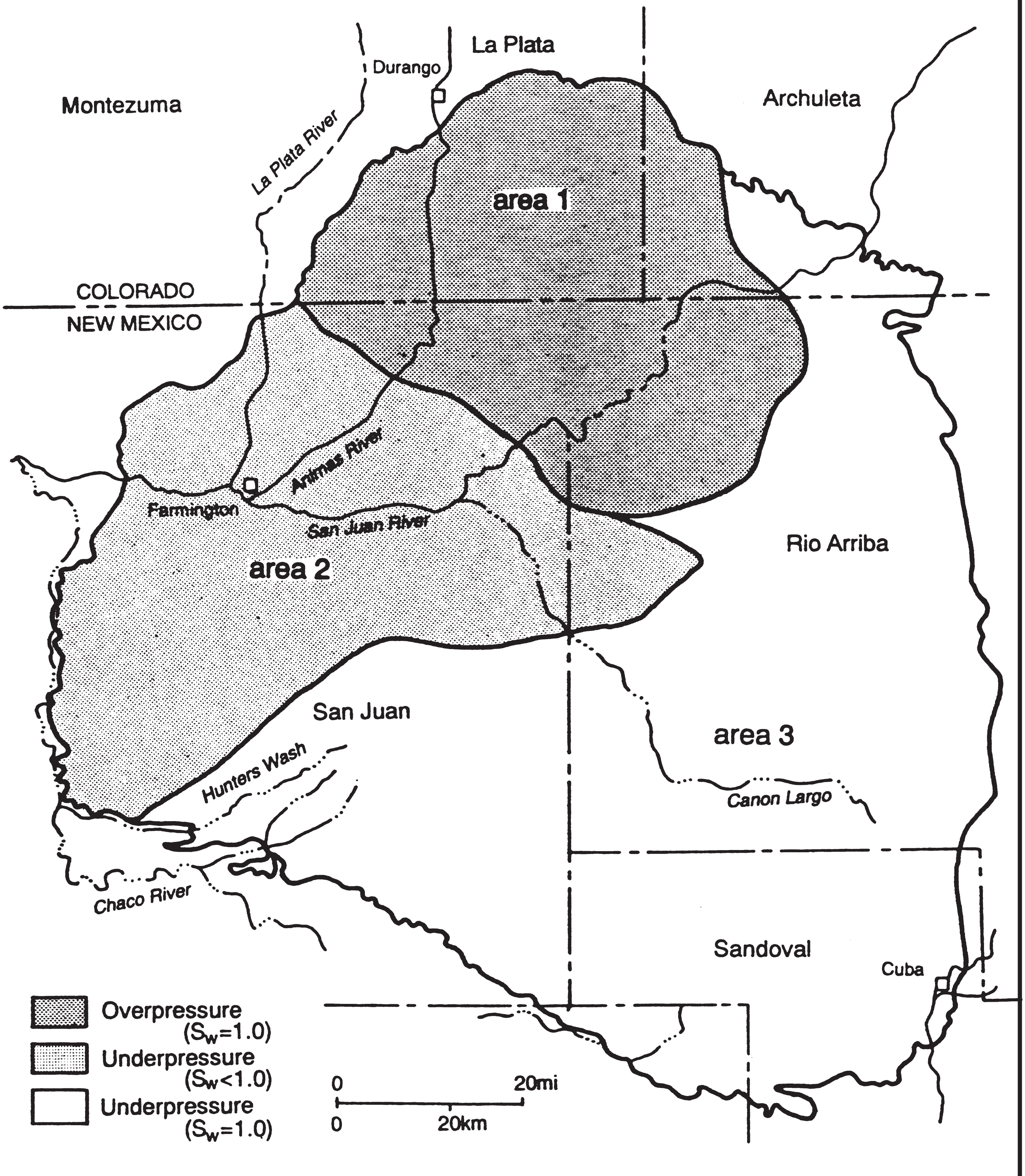
Cross Section E-W from Figure A1-3, a Stratigraphic Strike Section from the Southeastern San Juan Basin, Showing the Erosional Fruitland-Ojo Alamo Contact

The Kirtland Shale has been eroded and the Ojo Alamo rests unconformably on the Fruitland

(Ayers and Ambrose, 1990)

7/14/01 kk 1027-SJ-6.cdr

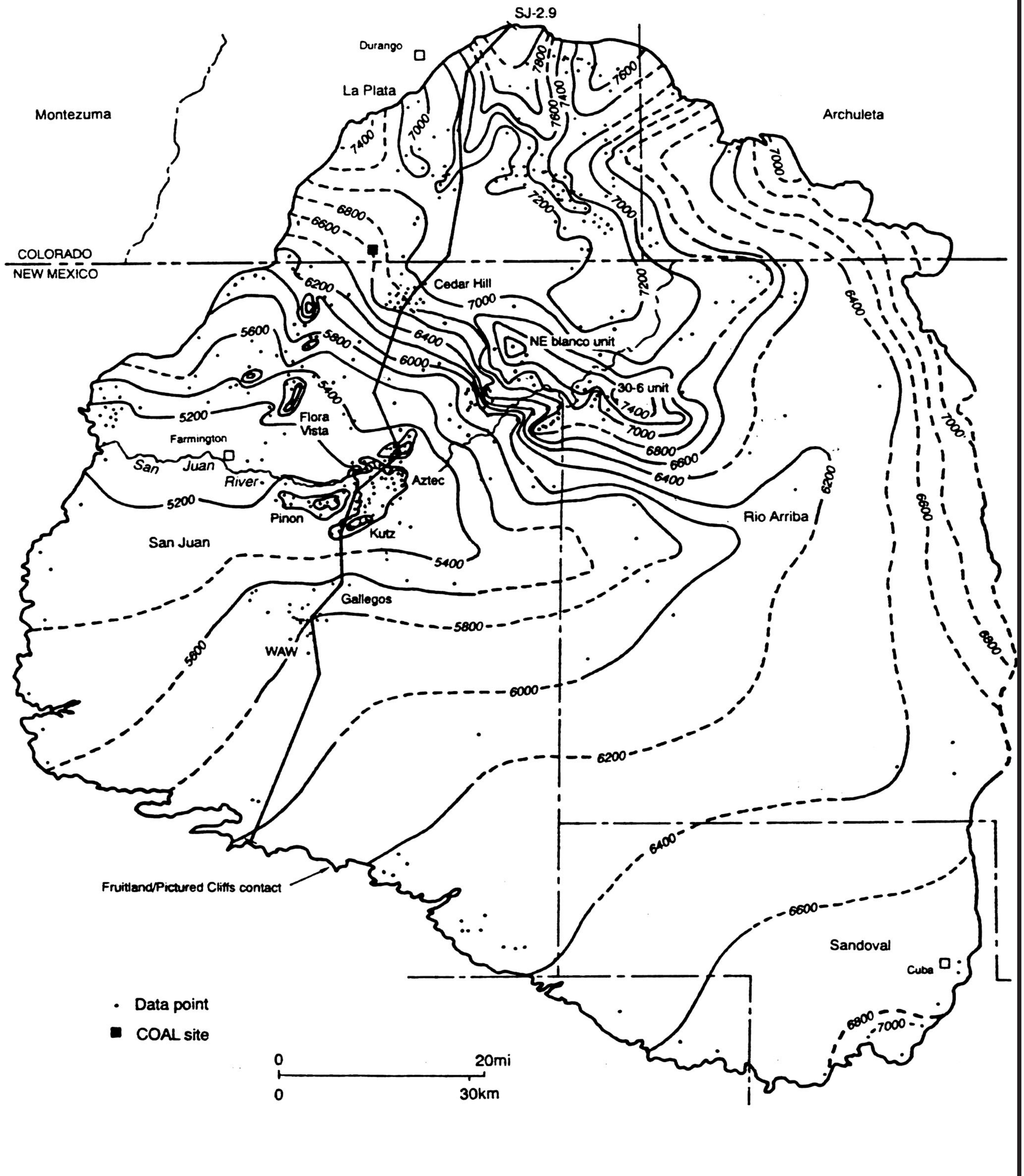
Figure A1-6



Areas of the San Juan Basin that Exhibit Similar Characteristics for Production, Coal Properties, and Hydrologic Pressure (New Mexico Bureau of Mines and Minerals, 1993)

7/14/01 kk 1027-SJ7.cdr

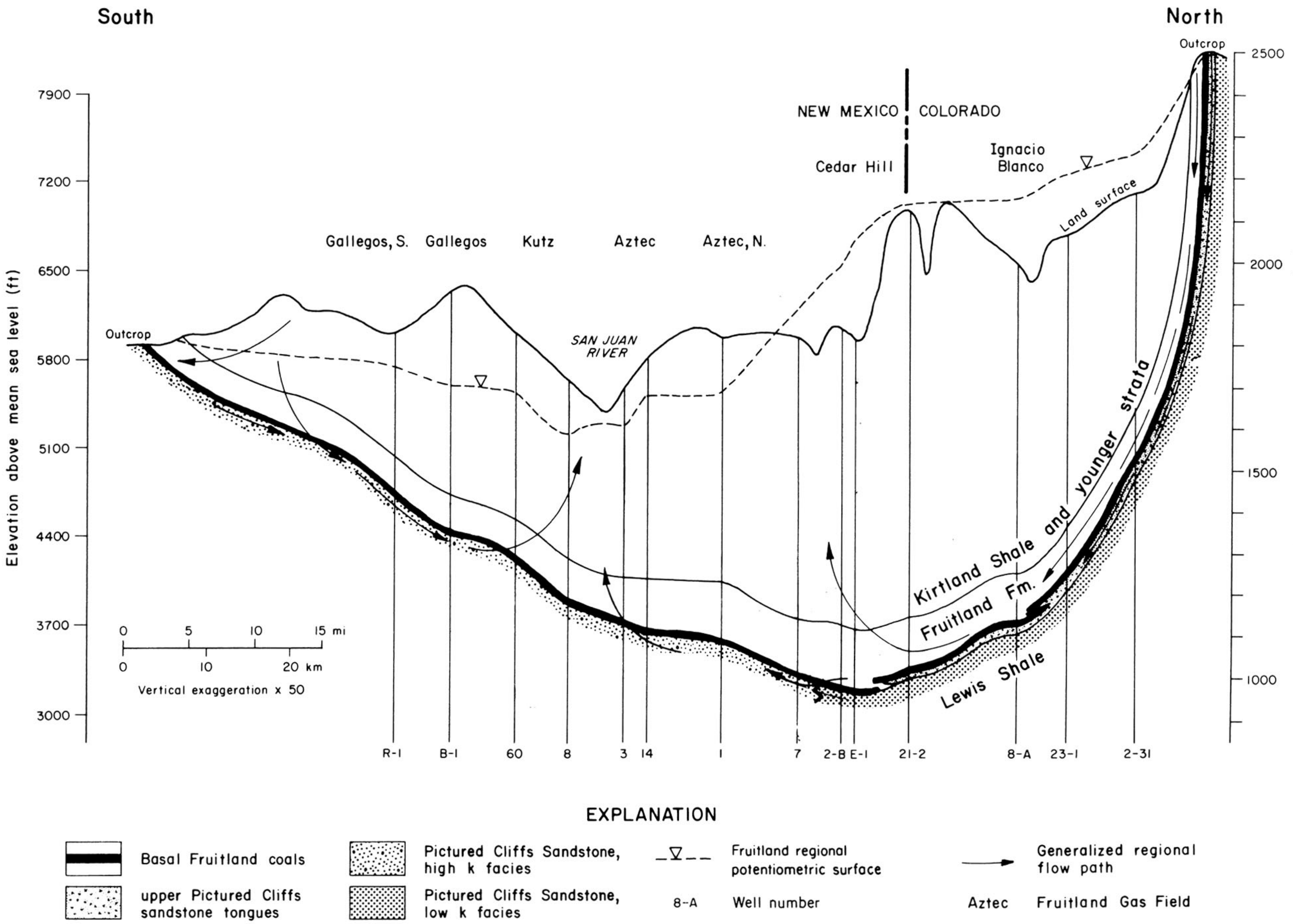
Figure A1-7



Map of the Potentiometric Surface of the Fruitland Aquifer (Kaiser et al., 1994)

7/14/01 kk 1027-SJ-08.cdr

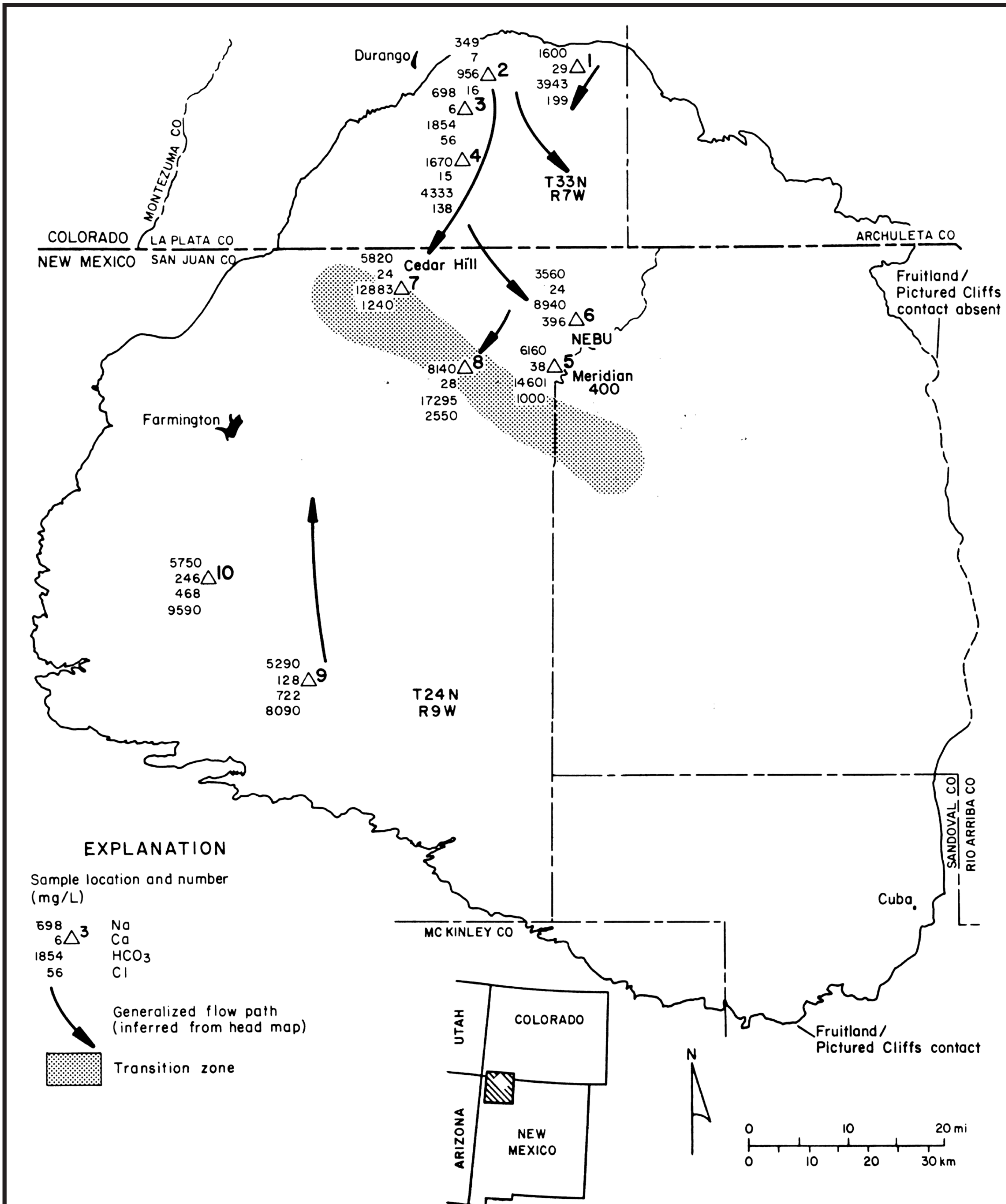
Figure A1-8



General Ground Water Flow in the Fruitland/Pictured Cliffs Aquifer System, San Juan Basin (Kaiser and Swartz, 1988)

7/14/01 kk 1027-SJ-09.cdr

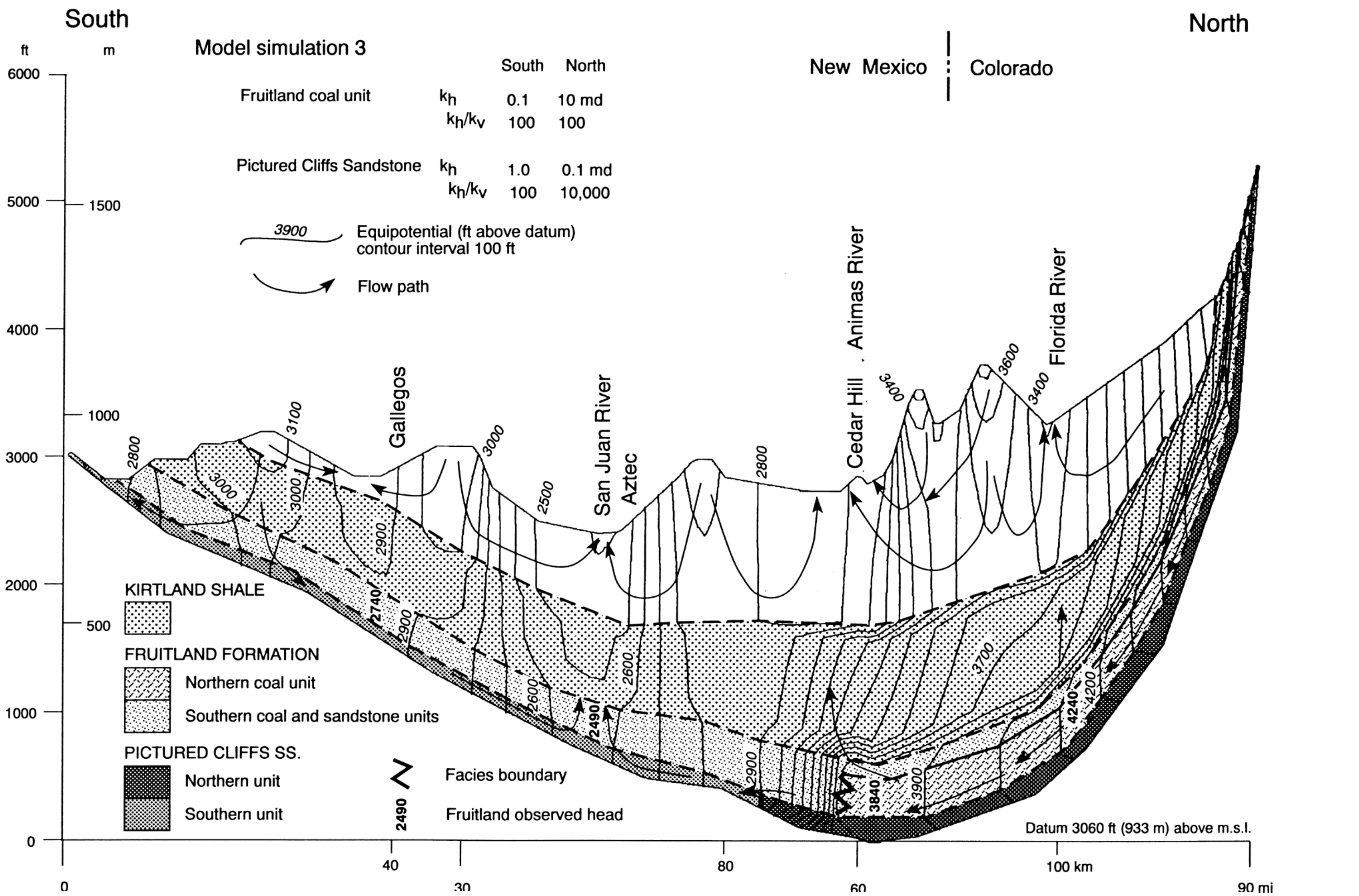
Figure A1-9



Generalized Flow Paths of the Fruitland/Pictured Cliffs Aquifer System, San Juan Basin
(Kaiser et al., 1994)

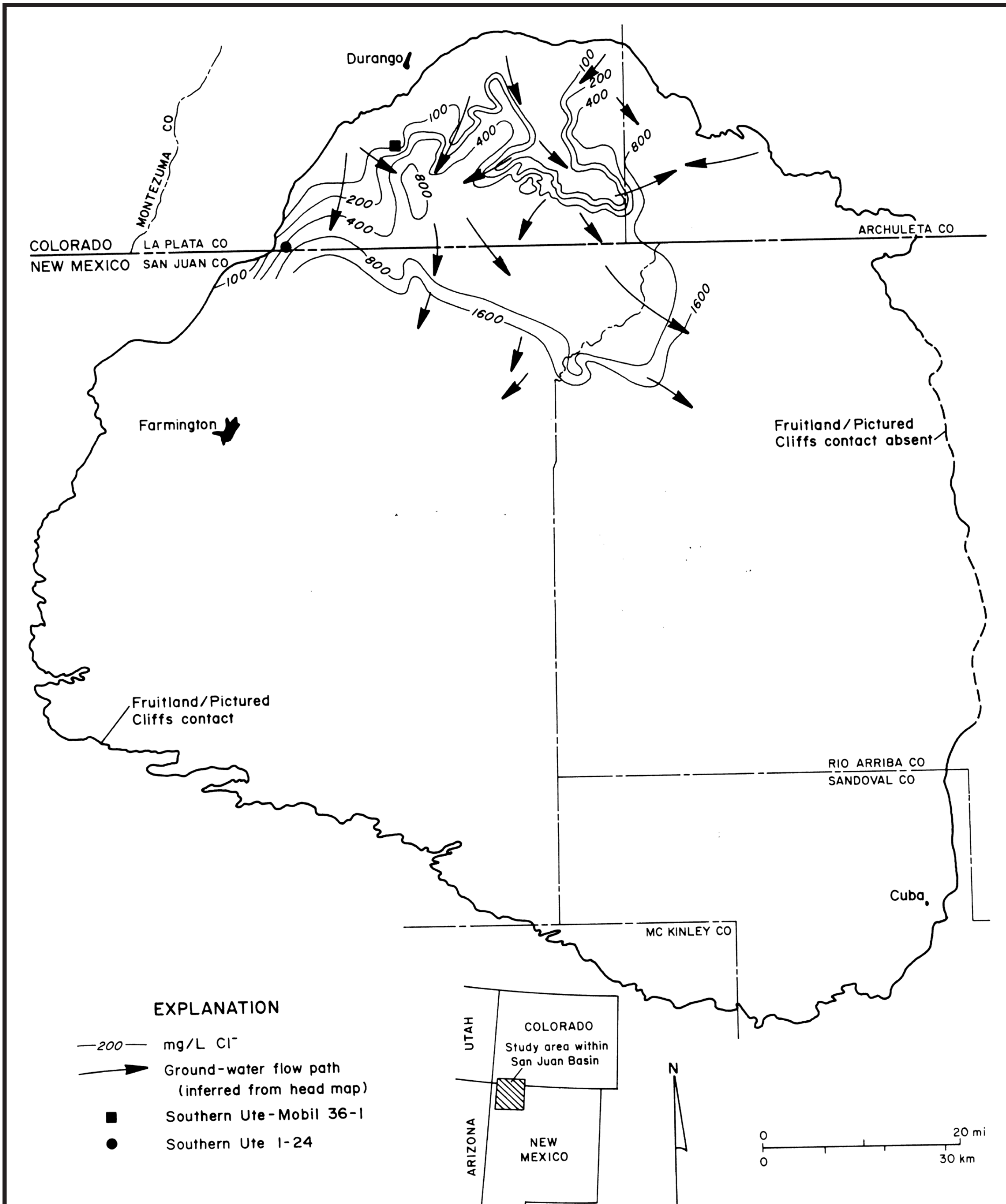
7/14/01 kk 1027-SJ-10.cdr

Figure A1-10



Equipotentials and Flow Paths from Ground Water Flow Modeling of the San Juan Basin (Kaiser et al., 1994)

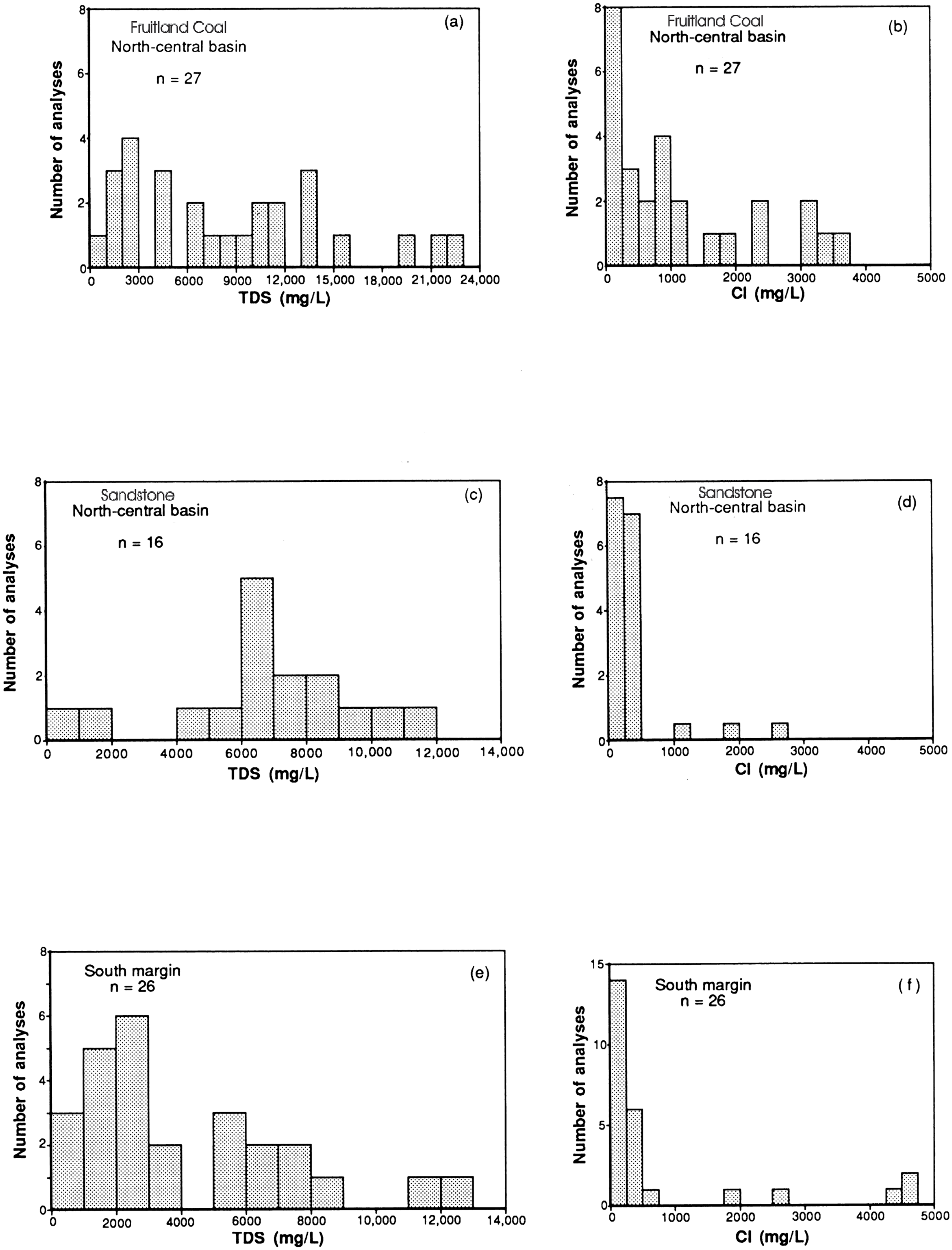
7/14/01 kk 1027-SJ-11.cdr	Figure A1-11



Chloride Concentration Map (mg/L) of Waters of the Fruitland Aquifer, San Juan Basin (Kaiser and Swartz, 1988)

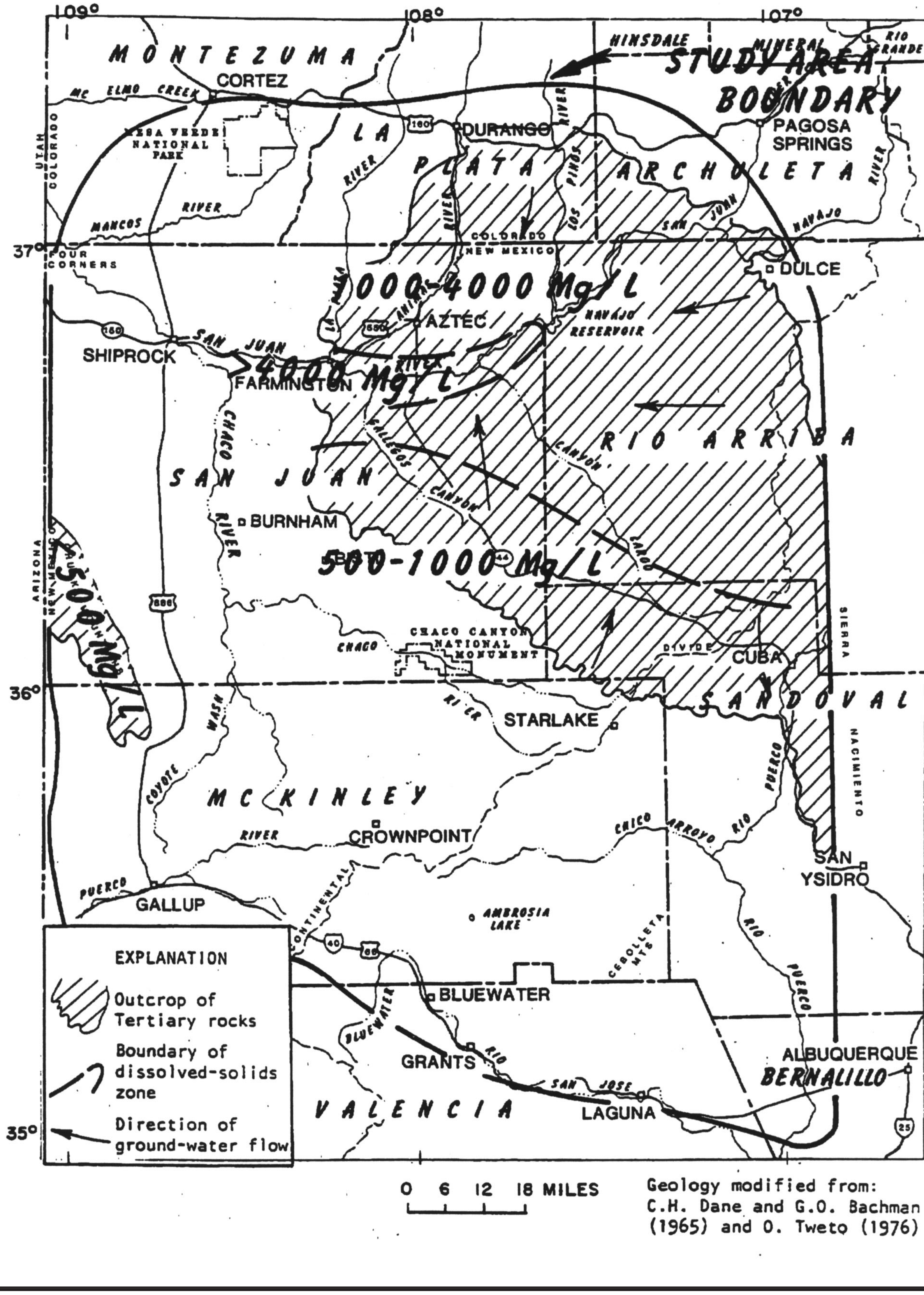
7/14/01 kk 1027-SJ-12.cdr

Figure A1-12



Histograms of Water Analyses (mg/L) from the Fruitland/Pictured Cliffs Aquifer System in the North Central and South-Margin Areas of the San Juan Basin
(Kaiser and Swartz, 1994)

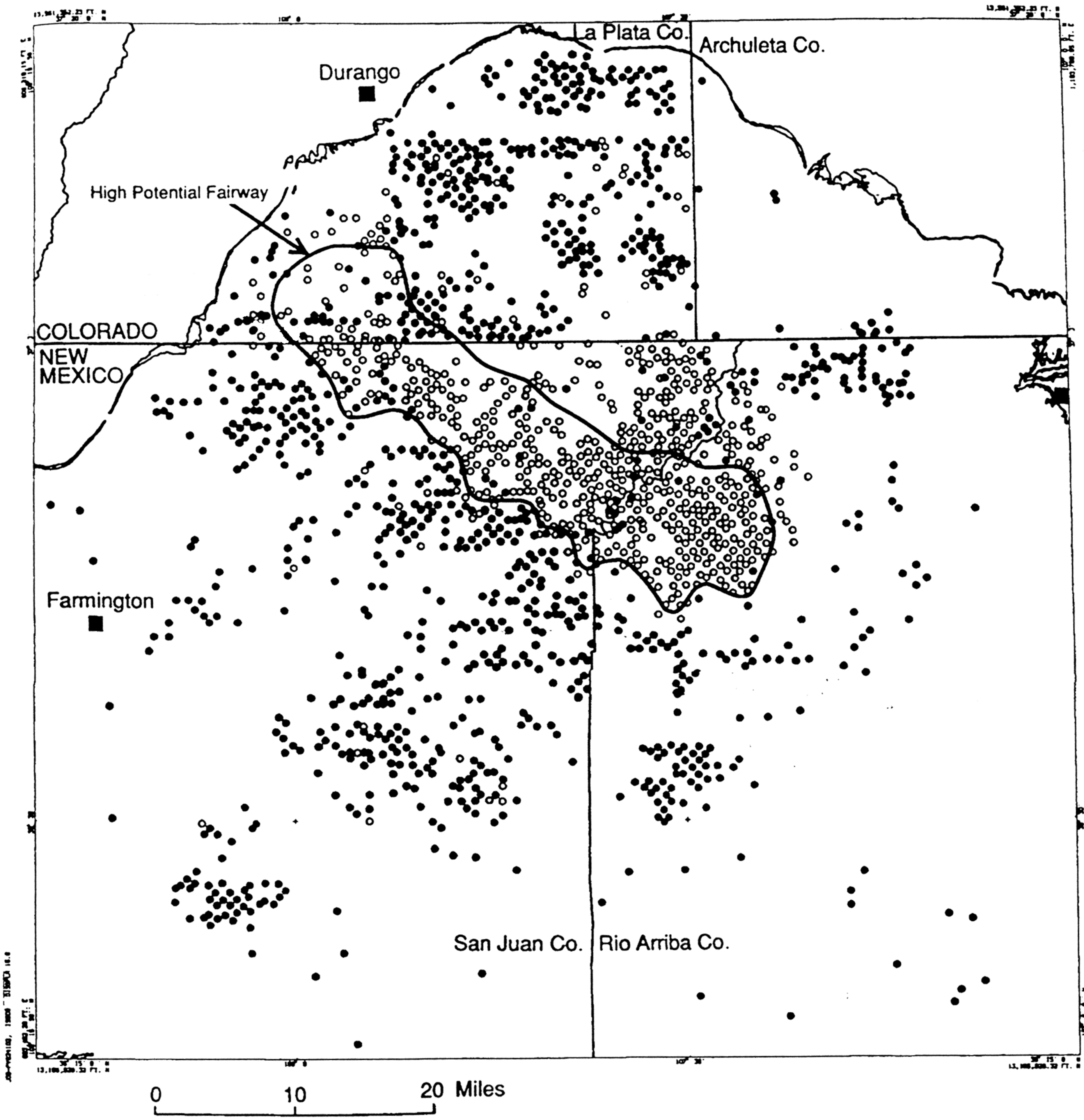
7/14/01 kk 1027-SJ-13.cdr	Figure A1-13



Direction of Ground Water Flow and Dissolved Solids Concentration in Tertiary Rocks (Lyford, 1979)

7/14/01 kk 1027-SJ-14.cdr

Figure A1-14

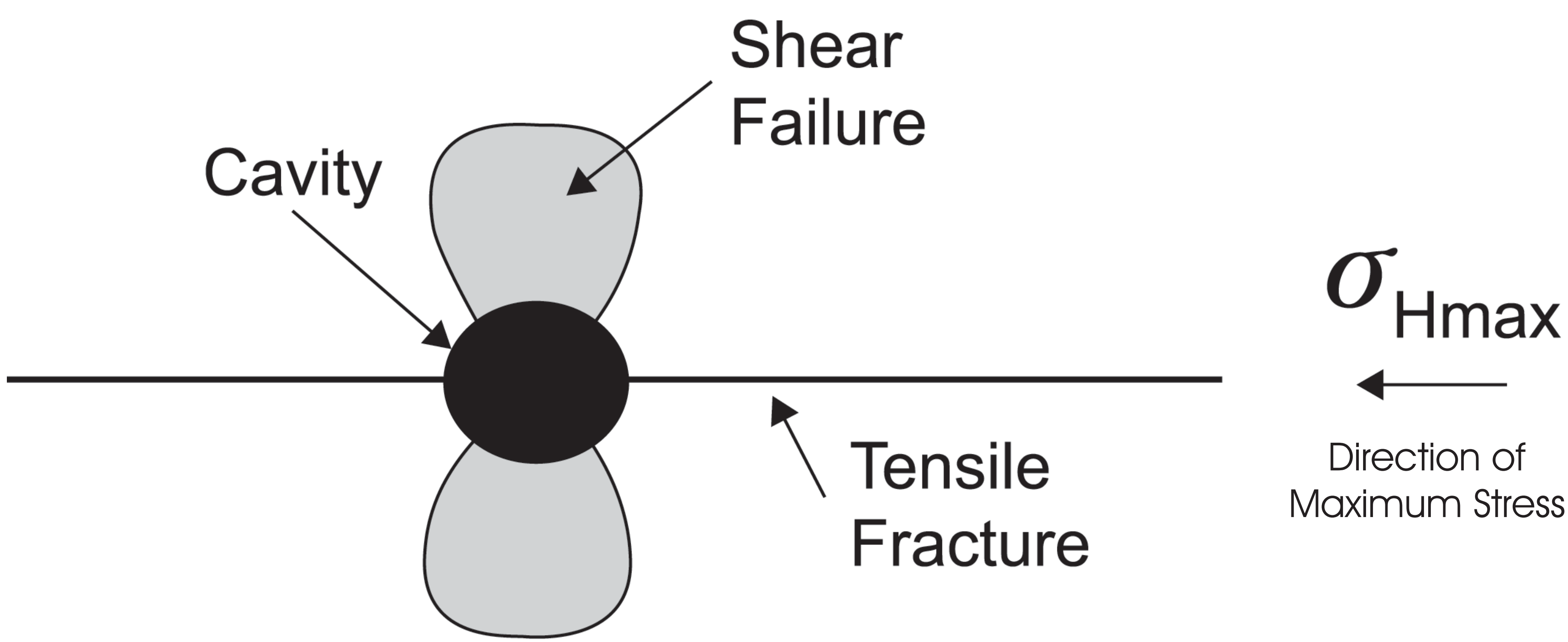


Outline of the Fairway Zone of Area 1 of the San Juan Basin

Filled dots represents wells using conventional fracturing treatments, and empty dots represent cavitation-cyclng completions

(Palmer et al., 1993)

7/14/01 kk 1027-SJ-15.cdr	Figure A1-15



Conceptual Schematic (Plan View) of Tensile Fracture and Shear Failure in Coal Formed by
Openhole Cavitation Cycling
(Khodaverian and McLennan, 1993)

7/14/01 kk 1027-SJ-16.cdr

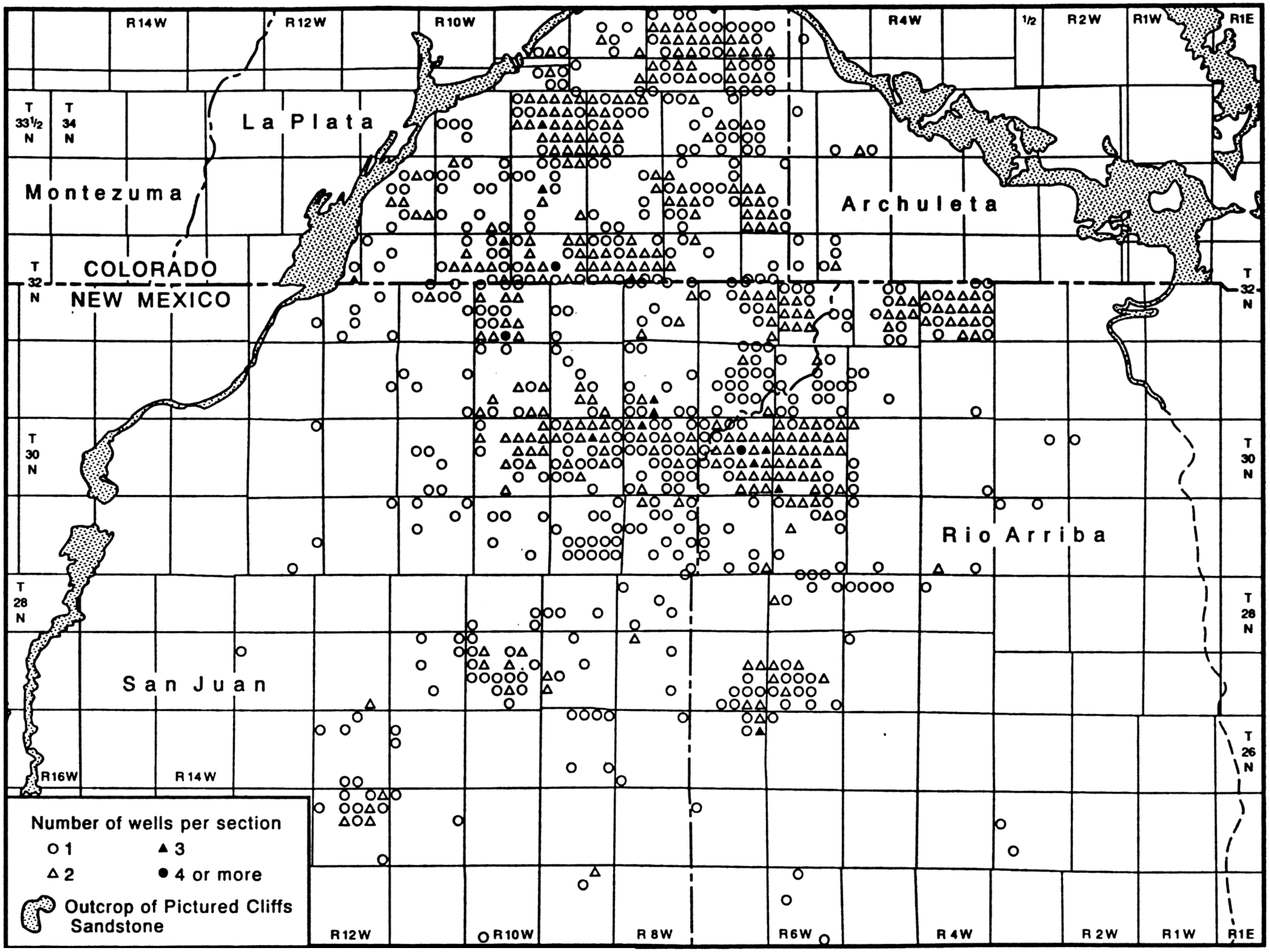
Figure A1-16

Cross-linked Gelled Sand Frac	
Water volume	2500 gal/ft of pay
Sand volume	5000 lbs/ft of pay
Type fluid	30# borate cross-linked gel
Type sand	40/70 mesh (1st 10% of job for fluid loss) 12/20 mesh (thereafter)
Avg. injection rate	55 BPM
Max. sand concentration	12 ppg
Pad volume	35% of total fluid pumped
Cost	\$50M–\$60M
Slick Water Sand Frac	
Water volume	4500 gal/ft of pay
Sand volume	3500 lbs/ft of pay
Type fluid	fresh water w/friction reducer
Type sand	20/40 mesh
Avg. injection rate	100 bpm
Max. sand concentration	6 ppg
Pad volume	66% of total fluid pumped
Cost	\$25M–\$35M
Foam Frac (gelled water)	
Water volume	2000 gal/ft of pay
Sand volume	5000 lbs/ft of pay
Type fluid	30# borate cross-linked gel
Type sand	100 mesh (1st 14% of job for fluid loss) 12/20 mesh (thereafter)
Avg. injection rate	40 BPM
Max. sand concentration	6 ppg
Pad volume	27% of total fluid pumped
Cost	\$100M–\$110M
Foam Frac (slick water)	
Water volume	2650 gal/ft of pay
Sand volume	3200 lbs/ft of pay
Type fluid	fresh water w/friction reducer
Type sand	40/70 mesh (1st 10% of job for fluid loss) 20/40 mesh (thereafter)
Avg. injection rate	90 BPM
Max. sand concentration	6 ppg
Pad volume	64% of total fluid pumped
Cost	\$75M–\$85M

Table of Fracture Stimulation Treatments in the Fruitland Formation of the San Juan Basin (Palmer et al., 1993)

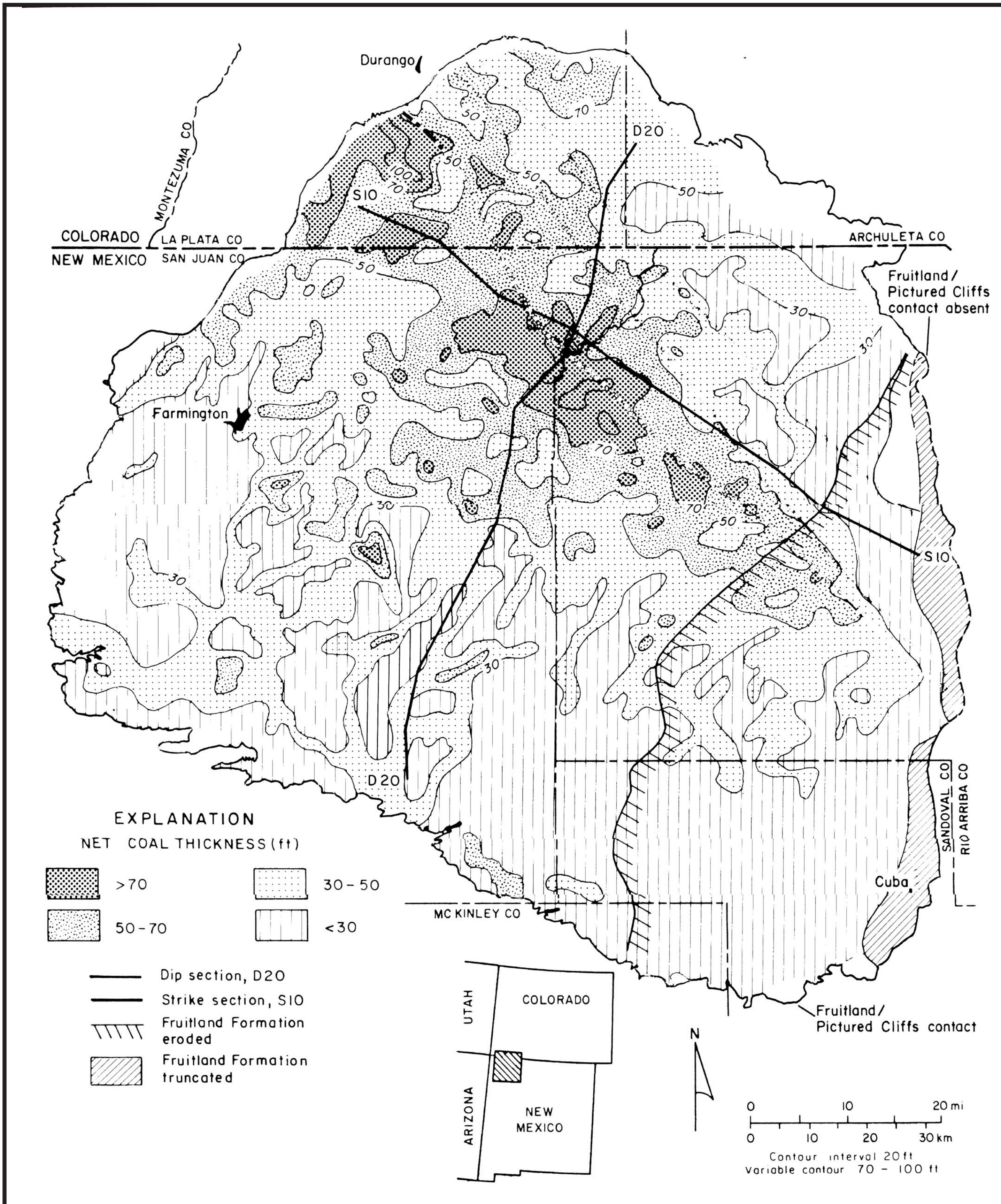
7/14/01 kk 1027-SJ-17.cdr

Figure A1-17



Density of Wells in the Northern Portion of Area 1 in the San Juan Basin, as of 12/31/1990
(New Mexico Bureau of Mines, 1993)

7/14/01 kk 1027-SJ-18.cdr	Figure A1-18



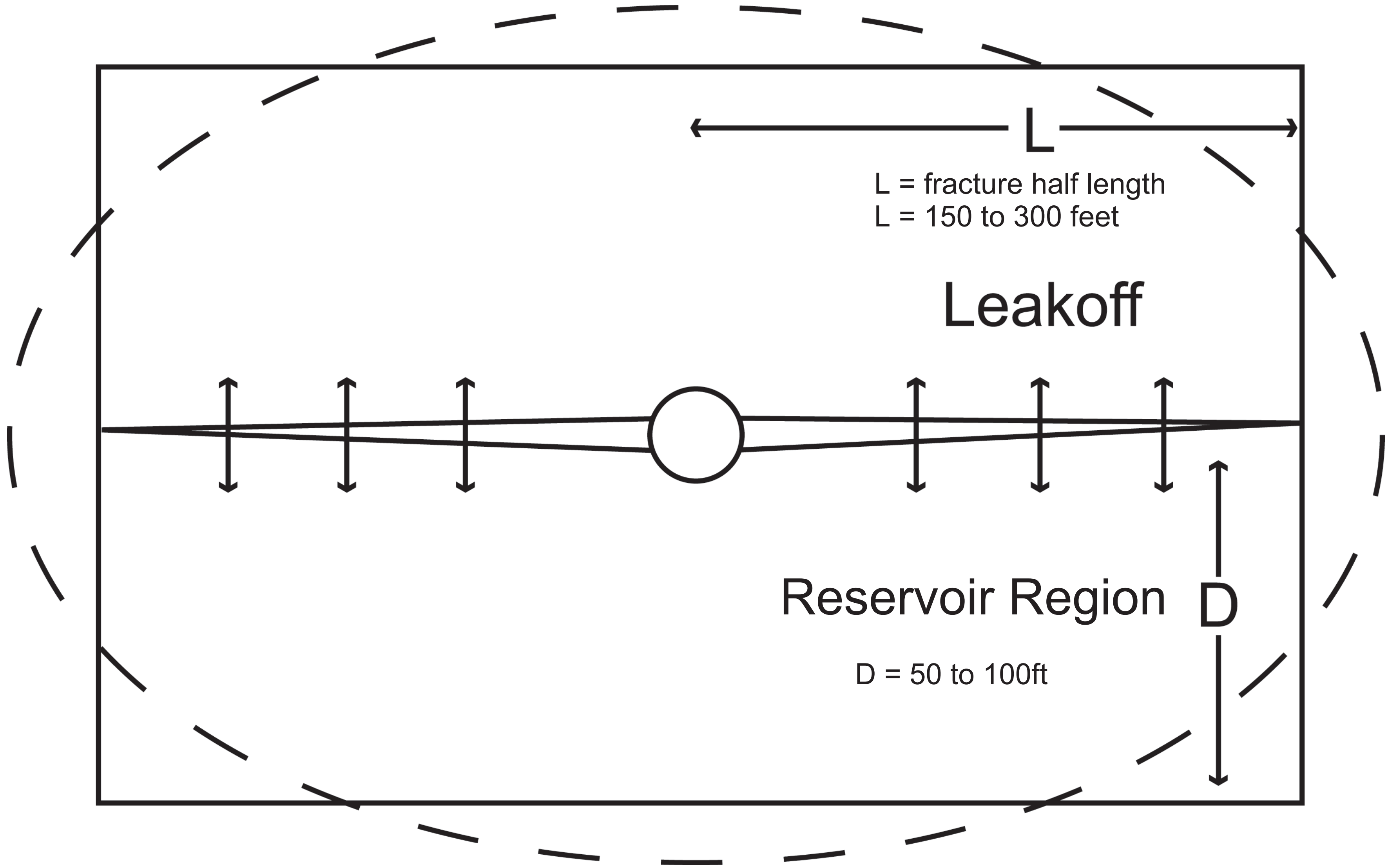
Fruitland Net Coal Map.

Note: Cross Sections D20 and S10 are Shown in Figures A1-4 and A1-5

(Ayers and Ambrose, 1990)

7/14/01 kk 1027-SJ-19.cdr

Figure A1-19



Plan View of a Vertical, Two-Winged Coalbed Methane Fracture Showing the Reservoir Region Invaded by Fracturing Fluid Leakoff (Palmer et al., 1991).

7/14/01 kk 1027-SJ-20.cdr

Figure A1- 20